Transverse spin physics at COMPASS

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on behalf of the COMPASS collaboration

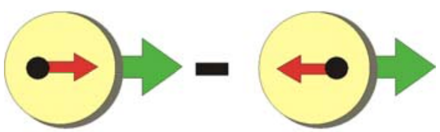
<u>Outline</u>

- Transversity measurements at COMPASS
    - Collins effect
    - hadron pair asymmetry
- Sivers effect
- Prospects at COMPASS

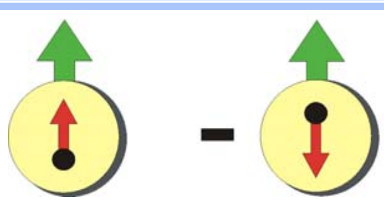
Transversity

At leading order, the inner structure of the nucleon can be described with three **Parton Distribution Function** (PDF):

$q(x)$ momentum distribution: describes the probability of finding a quark with a fraction x of the nucleon momentum;



$\Delta q(x)$ helicity distribution : describes the probability, in a longitudinal polarized nucleon (w.r.t. the direction of motion), of finding a quark with spin parallel to the nucleon spin;



$\Delta_T q(x)$ transversity distribution : describes the probability, in a transversely polarized nucleon (w.r.t. the direction of motion), of finding a quark with spin parallel to the nucleon spin;

Transversity in SIDIS

the Transversity DF is chiral-odd:

observable effects are given only by the product of $\Delta_T q\ (x)$ and an other chiral-odd function

can be measured in SIDIS on a transversely polarized target via “quark polarimetry”

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$l\,N^{\uparrow} \rightarrow l'\,h\,X$ **"Collins" asymmetry**

"Collins" Fragmentation Function

$l\,N^{\uparrow} \rightarrow l'\,h\,h\,X$ **hadron-pair asymmetry**

"Interference" Fragmentation Function

$l\,N^{\uparrow} \rightarrow l'\,\Lambda\,X$ **Λ polarisation**

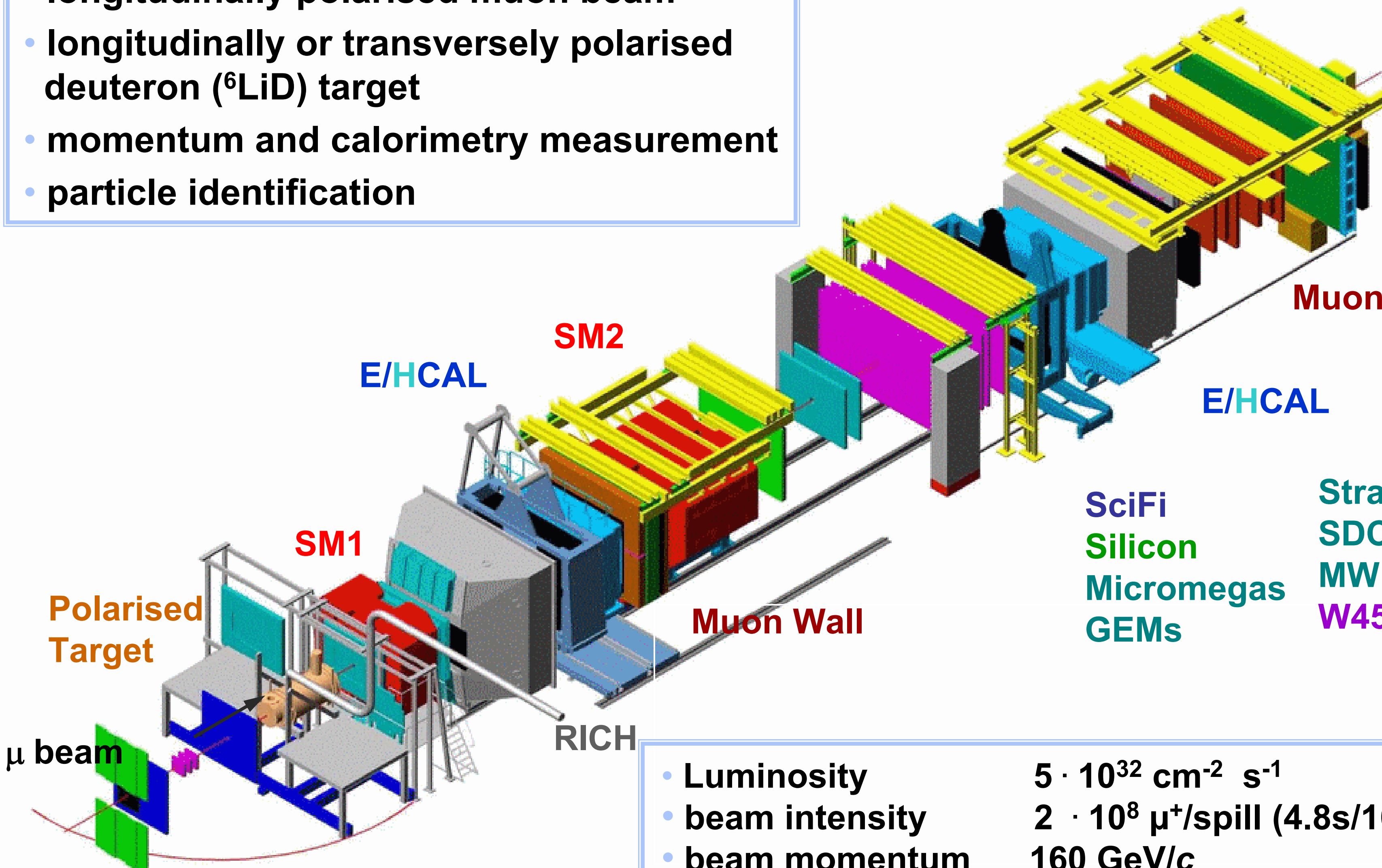
Fragmentation Function of $q^{\uparrow} \rightarrow \Lambda$

....

All these channels measured at COMPASS

COMPASS spectrometer 2002-2004

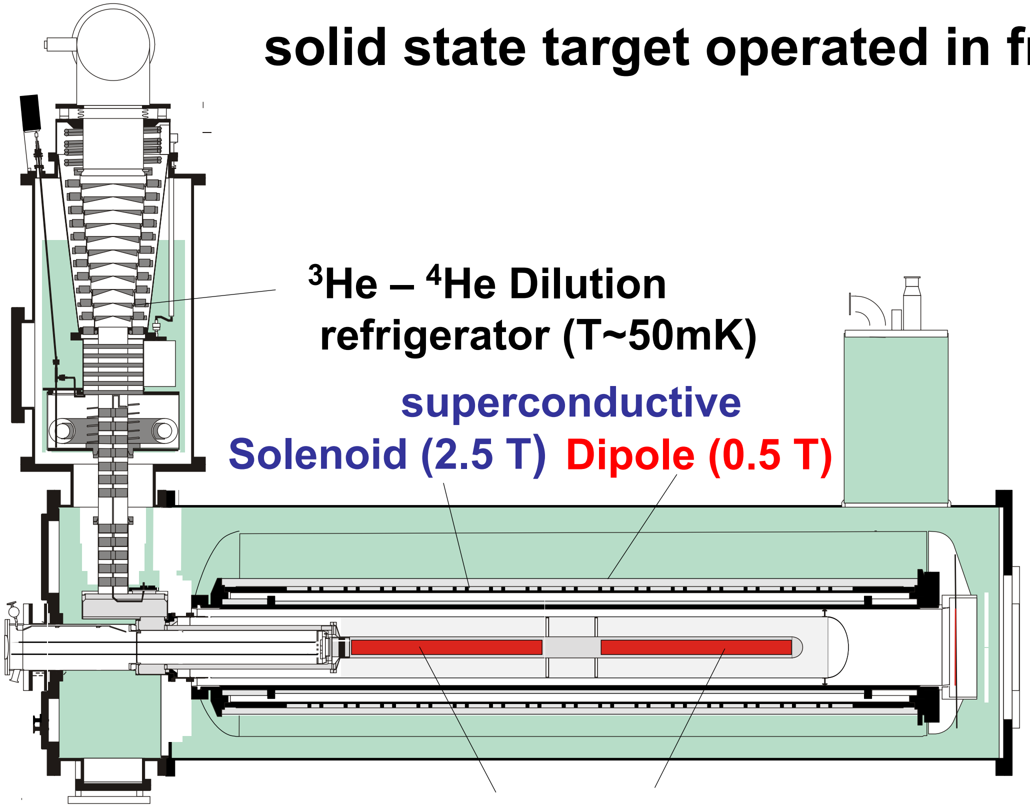
- longitudinally polarised muon beam
- longitudinally or transversely polarised deuteron (^{6}LiD) target
- momentum and calorimetry measurement
- particle identification



- Luminosity $5 \cdot 10^{32}$ cm^{-2} s^{-1}
- beam intensity $2 \cdot 10^{8}$ μ^{+}/spill (4.8s/16.8s)
- beam momentum 160 GeV/*c*

The COMPASS polarized target

solid state target operated in frozen spin mode



two 60 cm long cells
with opposite polarization
(to reduce systematics)

<u>2002-2004 data taking:</u>

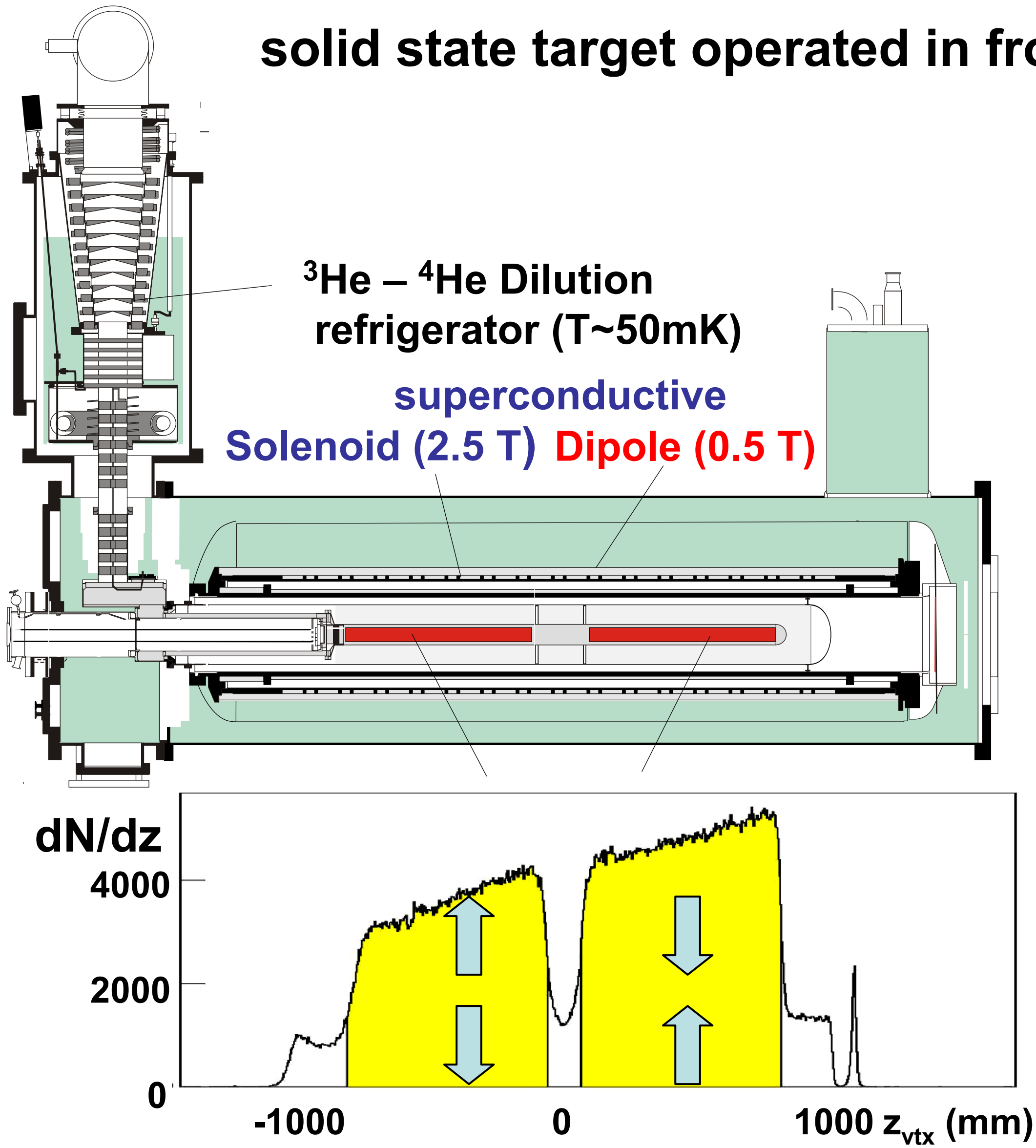
target material: ^{6}LiD

- **polarization ~ 50%**
- **dilution factor ~ 0.38**

<u>2007</u>: Data taking with a transversely polarised proton target (NH_3)

The COMPASS polarized target

solid state target operated in frozen spin mode



<u>2002-2004 data taking:</u>

target material: ^6LiD

- **polarization ~ 50%**
- **dilution factor ~ 0.38**

2 configurations:
reversed once a week
(relaxation time > 2000h)

Data selection

DIS cuts:

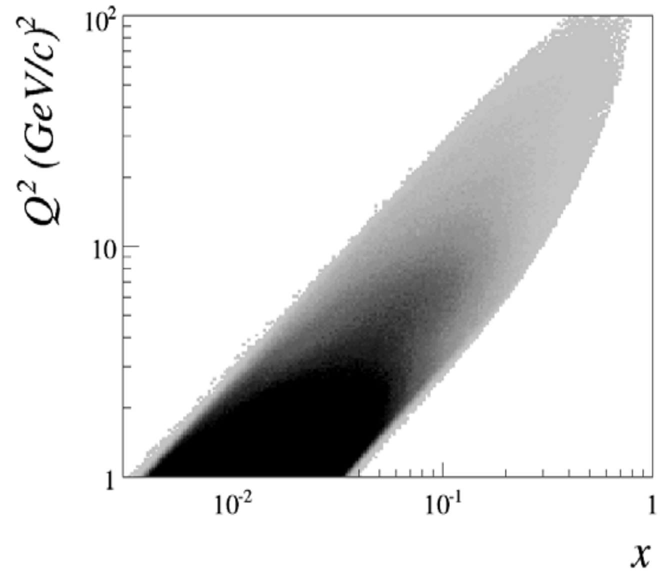
- $Q^2 > 1\ (GeV/c)^2$
- $0.1 < y < 0.9$
- $W > 5\ GeV/c$

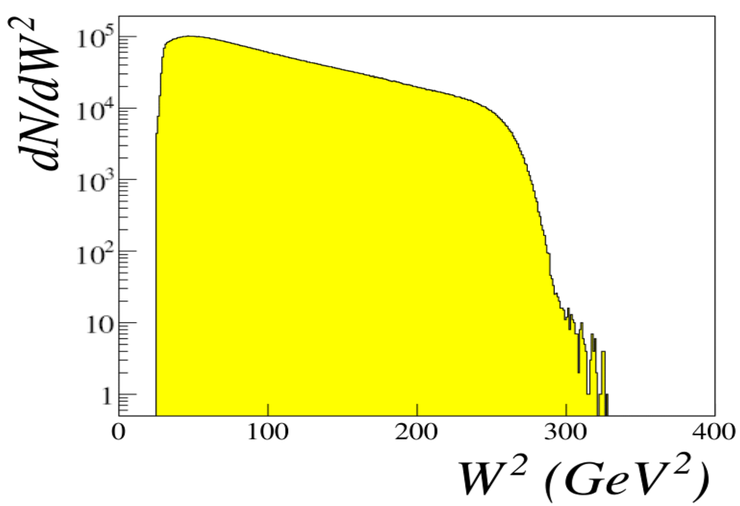
hadron selection:

- $z > 0.2$

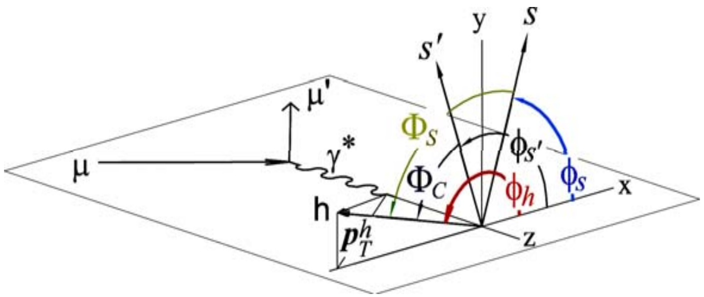
  ($z>0.25$ for leading hadron selection)
- $p_t > 0.1 GeV/c$

Statistics 2002 - 2004:
8.5 M positive hadrons
7.0 M negative hadrons





Collins asymmetries 2002-2004 data

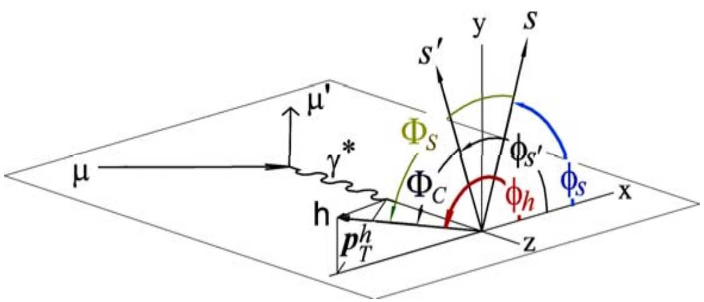


$\Phi_C = \phi_h - \phi_{s'}$ is the "Collins angle"

$$A_{Coll} = \frac{A_C^h}{f \cdot P_T \cdot D_{nn}} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

Information on Collins FF from Belle

Collins asymmetries 2002-2004 data



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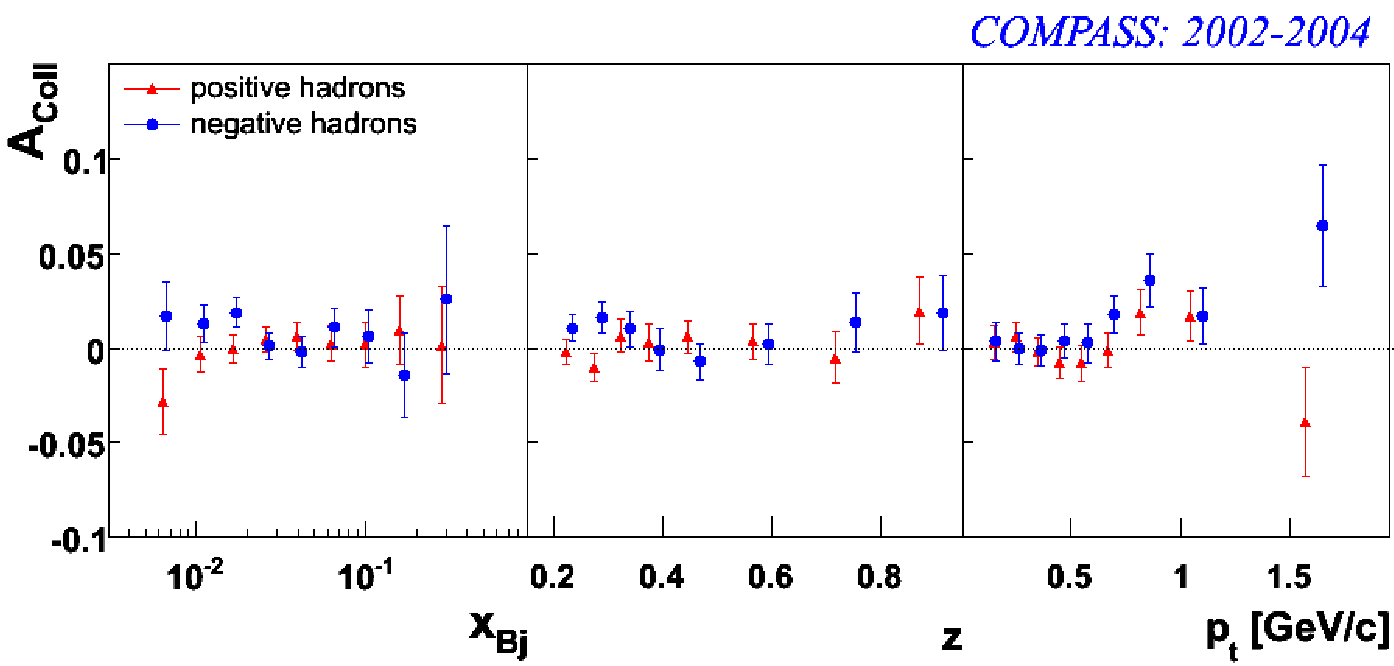

Final Results

all deuteron data

NP B765 (2007) 31-70

- **only statistical errors shown (systematic errors considerably smaller)**
- **small asymmetries**

Interpretation

- naïve interpretation of the results (parton model, valence region)

assuming all the hadron to be pions

$$A_{Coll}^{d,\pi^+} \simeq \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{4\Delta_T^0 D_1 + \Delta_T^0 D_2}{4D_1 + D_2}$$

$$A_{Coll}^{d,\pi^-} \simeq \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{\Delta_T^0 D_1 + 4\Delta_T^0 D_2}{D_1 + 4D_2}$$

Small asymmetries → **$\Delta_T u(x) + \Delta_T d(x) \sim 0$**

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expected even if $\Delta_T^0 D_2 \approx -\Delta_T^0 D_1$

suggested by data on proton target – HERMES experiment

$$A_{Coll}^{p,\pi^+} \simeq \frac{4\Delta_T u_v \Delta_T^0 D_1 + \Delta_T d_v \Delta_T^0 D_2}{4u_v D_1 + d_v D_2}$$

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$$A_{Coll}^{p,\pi^+} \simeq \frac{4\Delta_T u_v \Delta_T^0 D_1 + \Delta_T d_v \Delta_T^0 D_2}{4u_v D_1 + d_v D_2} \qquad A_{Coll}^{p,\pi^-} \simeq \frac{4\Delta_T u_v \Delta_T^0 D_2 + \Delta_T d_v \Delta_T^0 D_1}{4u_v D_2 + d_v D_1}$$

SIDIS measurements allow flavor separation analysis

→ Hadron identification is important

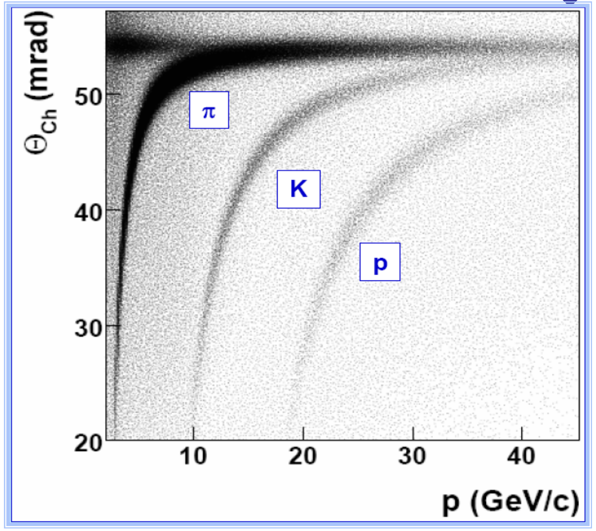
Hadron identification

Charged hadrons:

$\pi^{\pm}$ $K^{\pm}$

based on RICH response

(likelihood algorithm)



Cherenkov thresholds
- π ~ 3 GeV/c
- K ~ 9 GeV/c
- p ~ 17 GeV/c

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Charged hadrons:

$\pi^{\pm}$ **$K^{\pm}$**

based on RICH response

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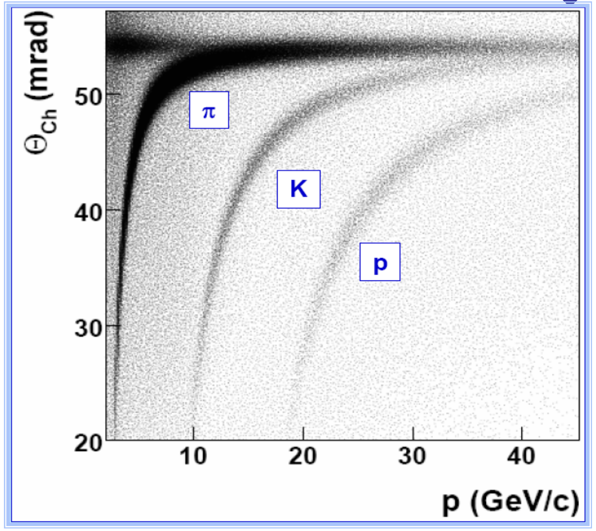
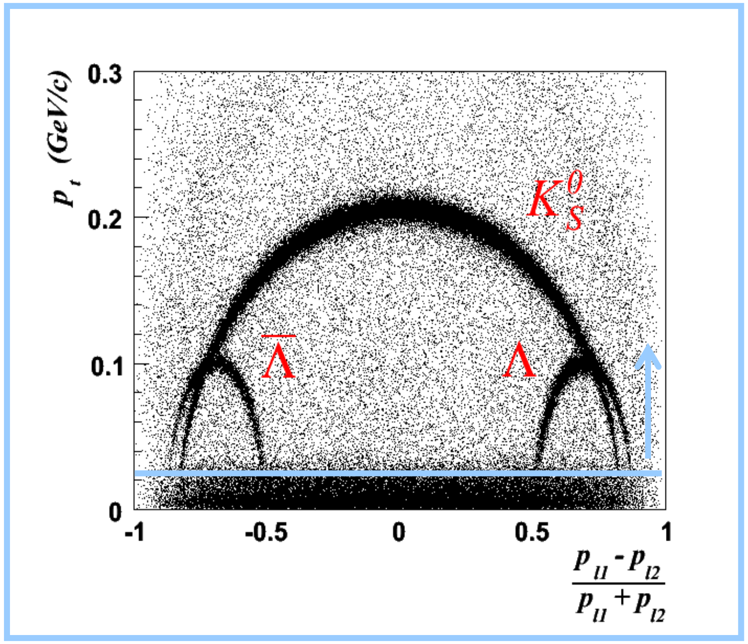


Neutral kaons **K^0**

- Secondary vertex with 2 outgoing tracks with opposite charge
- Target pointing (θ<10mrad)
- Cut on Armenteros plot
  (p_T^h > 25 MeV/c)



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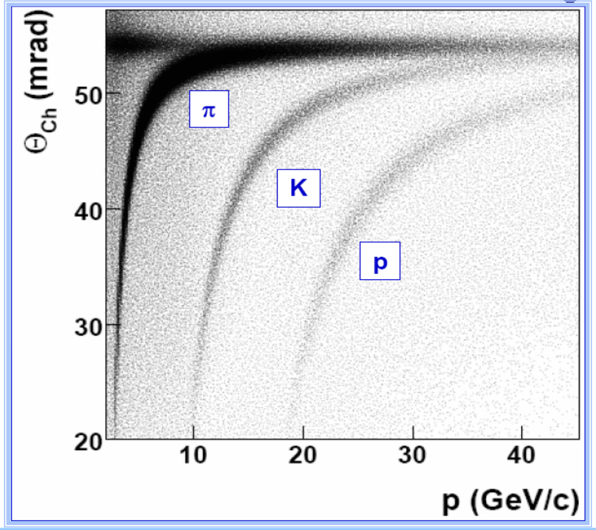

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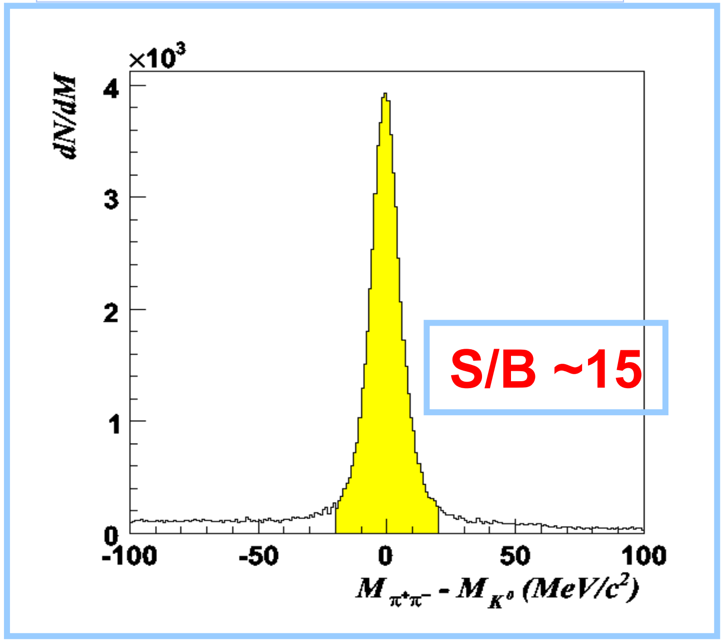

Hadron identification

Charged hadrons:

$\pi^{\pm}$ **$K^{\pm}$**

based on RICH response (likelihood algorithm)

Statistics 2003-2004:	positive	negative
π	5.2M	4.5M
K	0.9M	0.6M

Neutral kaons K^0

- Secondary vertex with 2 outgoing tracks with opposite charge
- Target pointing (θ<10mrad)
- Cut on Armenteros plot (p_T^h > 25 MeV/c)
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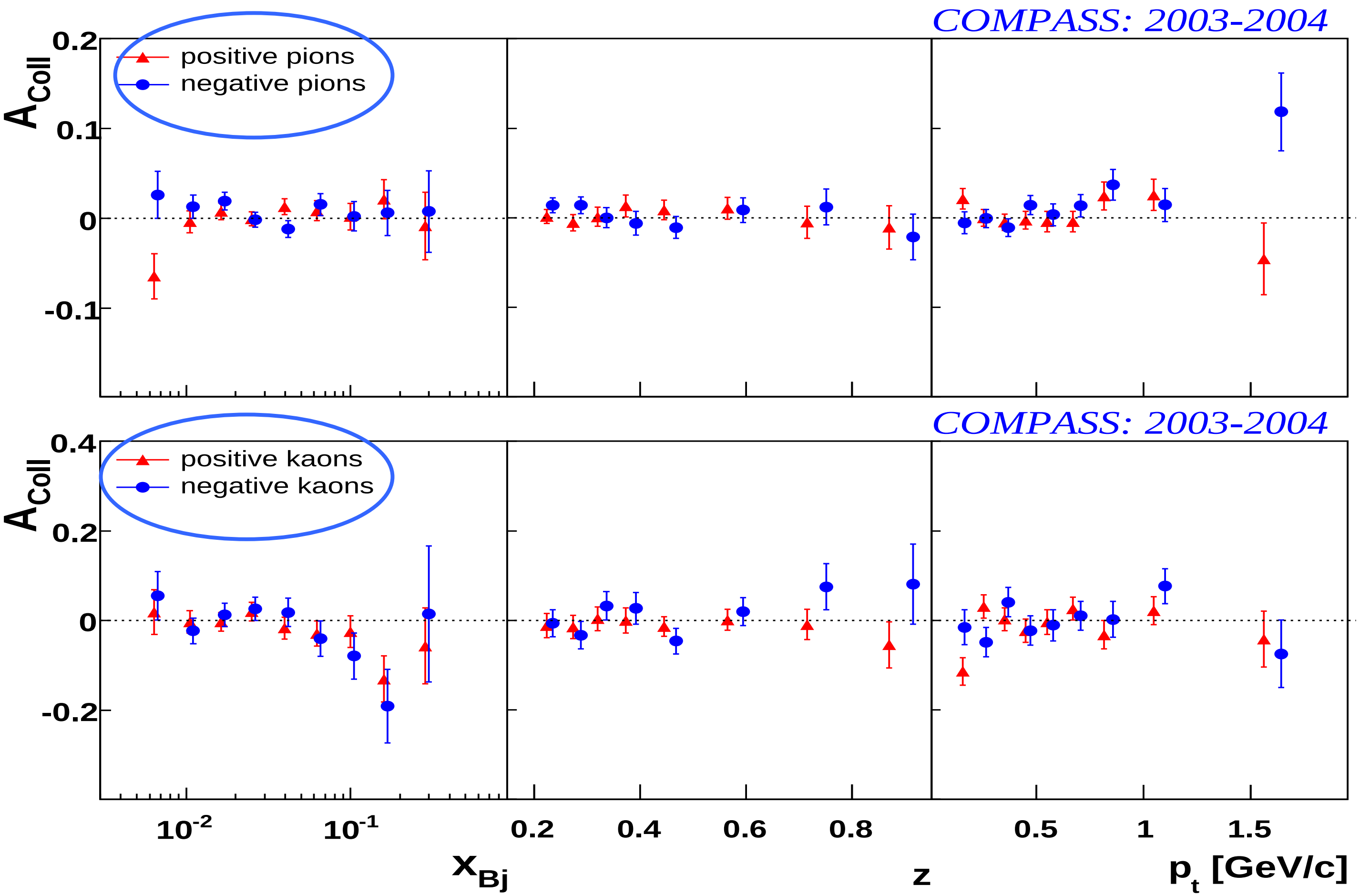
Statistics 2002-2004:	
K^0	0.26M

Collins asymmetries $\pi^{\pm}$ $K^{\pm}$



Final Results

all deuteron data

hep-ex/0802.2160

(subm. PLB)

- **only statistical errors shown (systematic errors considerably smaller)**
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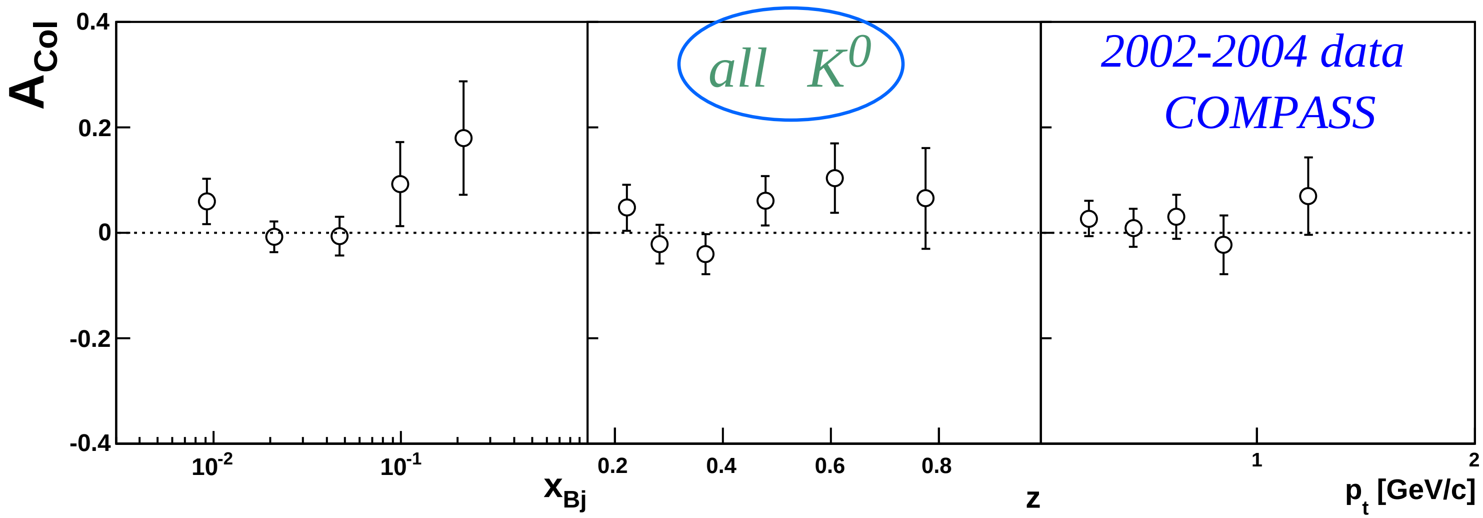
Collins asymmetries K^0



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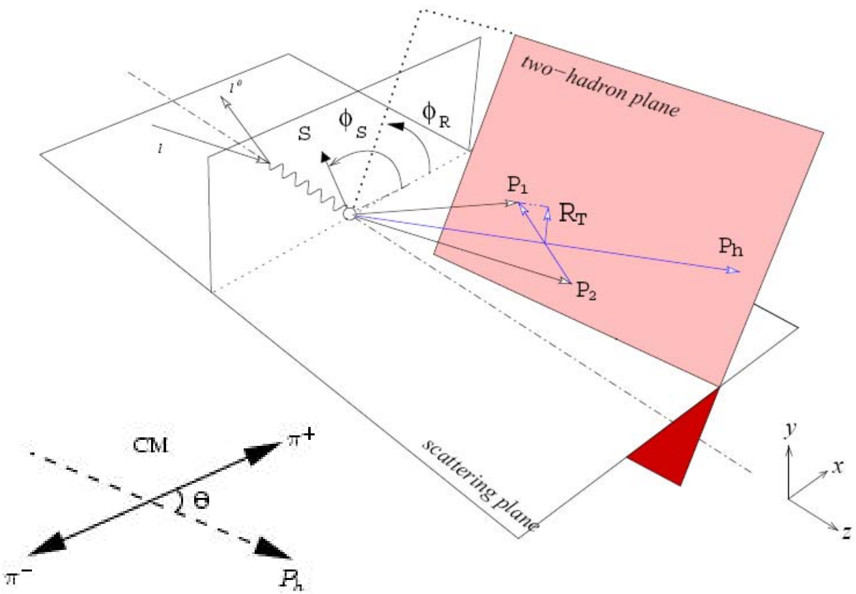
Two Hadrons Asymmetries



in inclusive production of hadron pairs, one can define the angle $\phi_{R\perp}$ and measure an azimuthal asymmetry from the modulation of the number of events in $\phi_{RS} = \phi_{R\perp} - \phi_S$,

$$N^{\pm}(\Phi_{RS}) = N^0 \cdot \{ 1 \pm A \cdot \sin\Phi_{RS} \}$$

Transversity distribution function

$$A_{RS} = \frac{1}{f \cdot P_T \cdot D} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{\angle}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, M_h^2)}$$

Interference fragmentation function presently unknown, being measured at BELLE

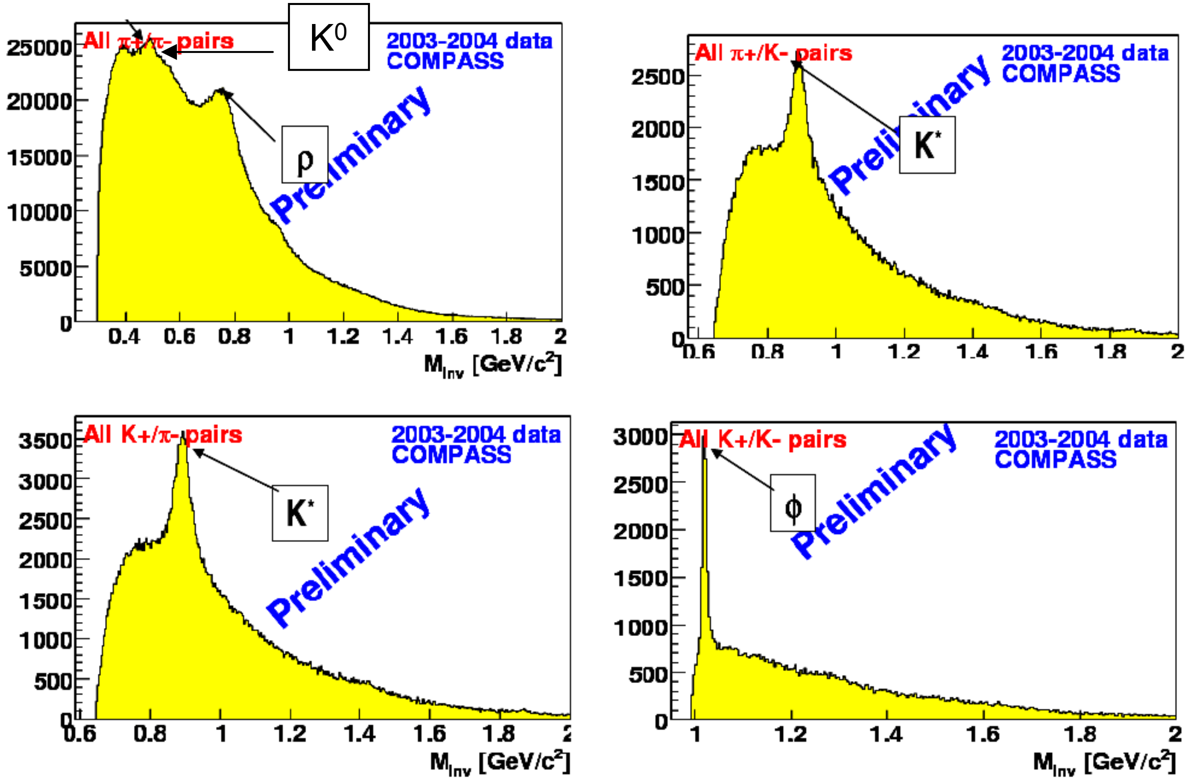
A. Bacchetta, M. Radici, hep-ph/0407345
X. Artru, hep-ph/0207309

Two Hadrons Asymmetries

2 different analysis:

1) **hadron pairs ordered with charge**:

	without PID	π+ π-	π+ K-	K+ π-	K+ K-
total	$5.3*10^6$	$3.7*10^6$	$2.4*10^5$	$3.0*10^5$	$8.7*10^4$



Different hadron combination → different invariant mass spectra

Two Hadrons Asymmetries

2) **z-ordered pairs**: select in the event the two hadrons with the highest relative energy z:

for leading hadron pairs the signal enhancement is predicted, hadrons with higher energy carry more information about the fragmenting quark polarization

16 combinations, 4 particle combinations times 4 charge combinations

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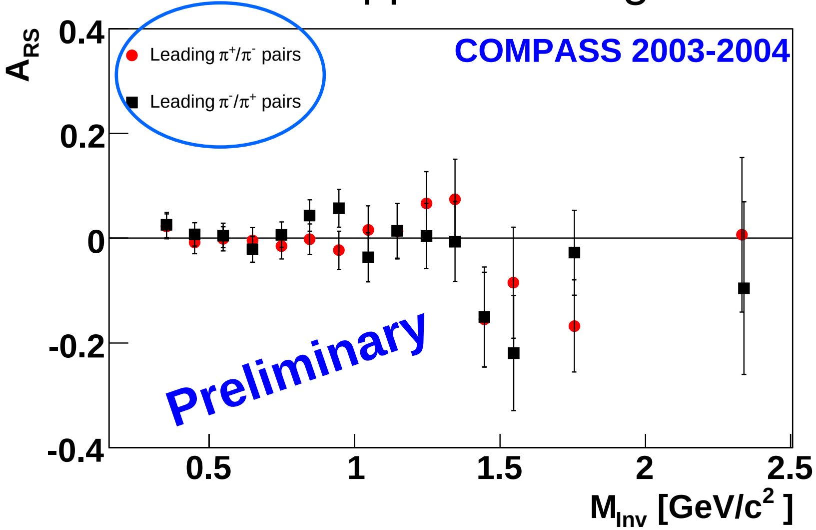
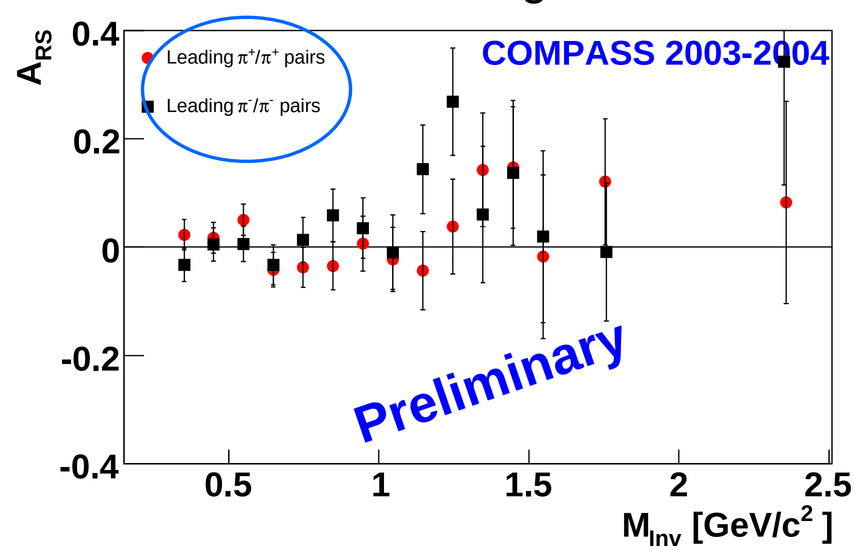
π with opposite charge

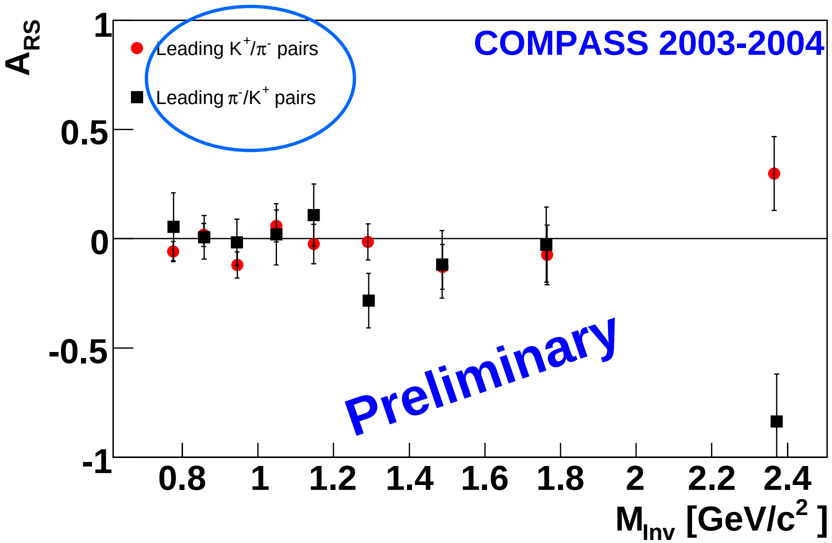


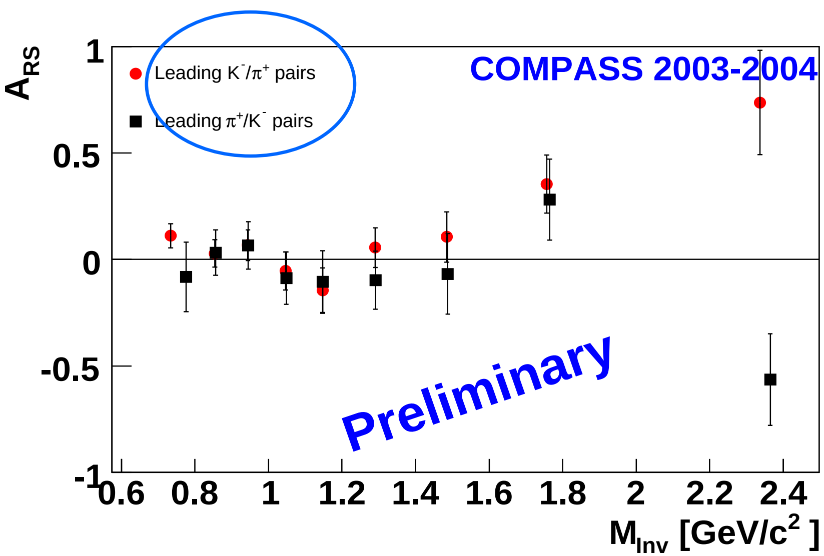
π with same charge



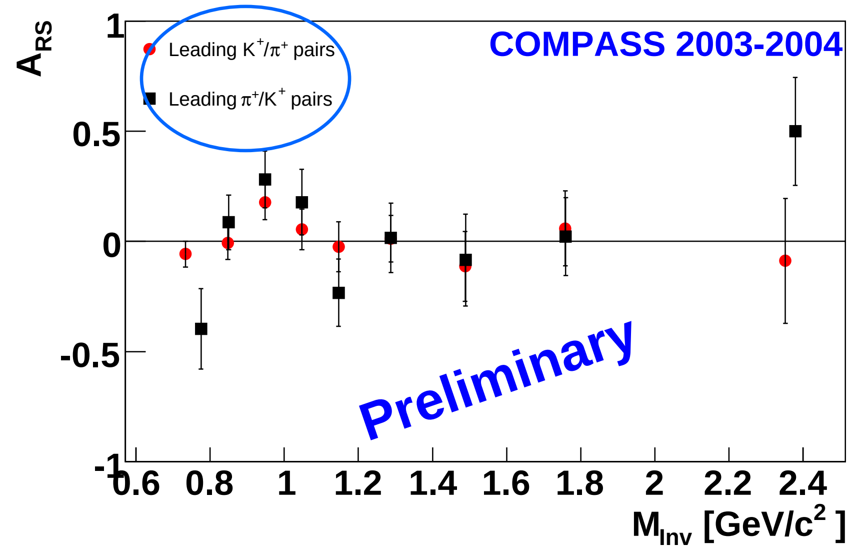
Two Hadrons Asymmetries

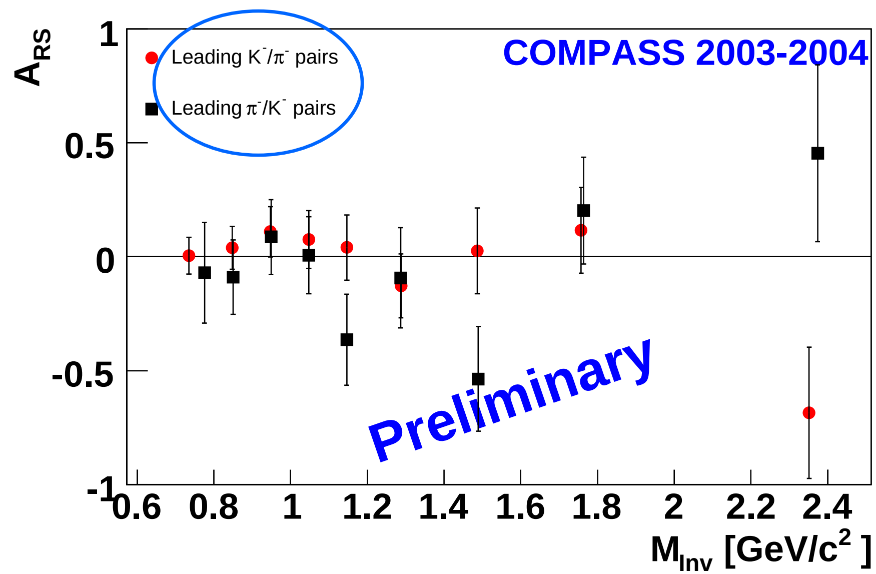
K/π and π/K with opposite charge





K/π and π/K with same charge





SIVERS mechanism

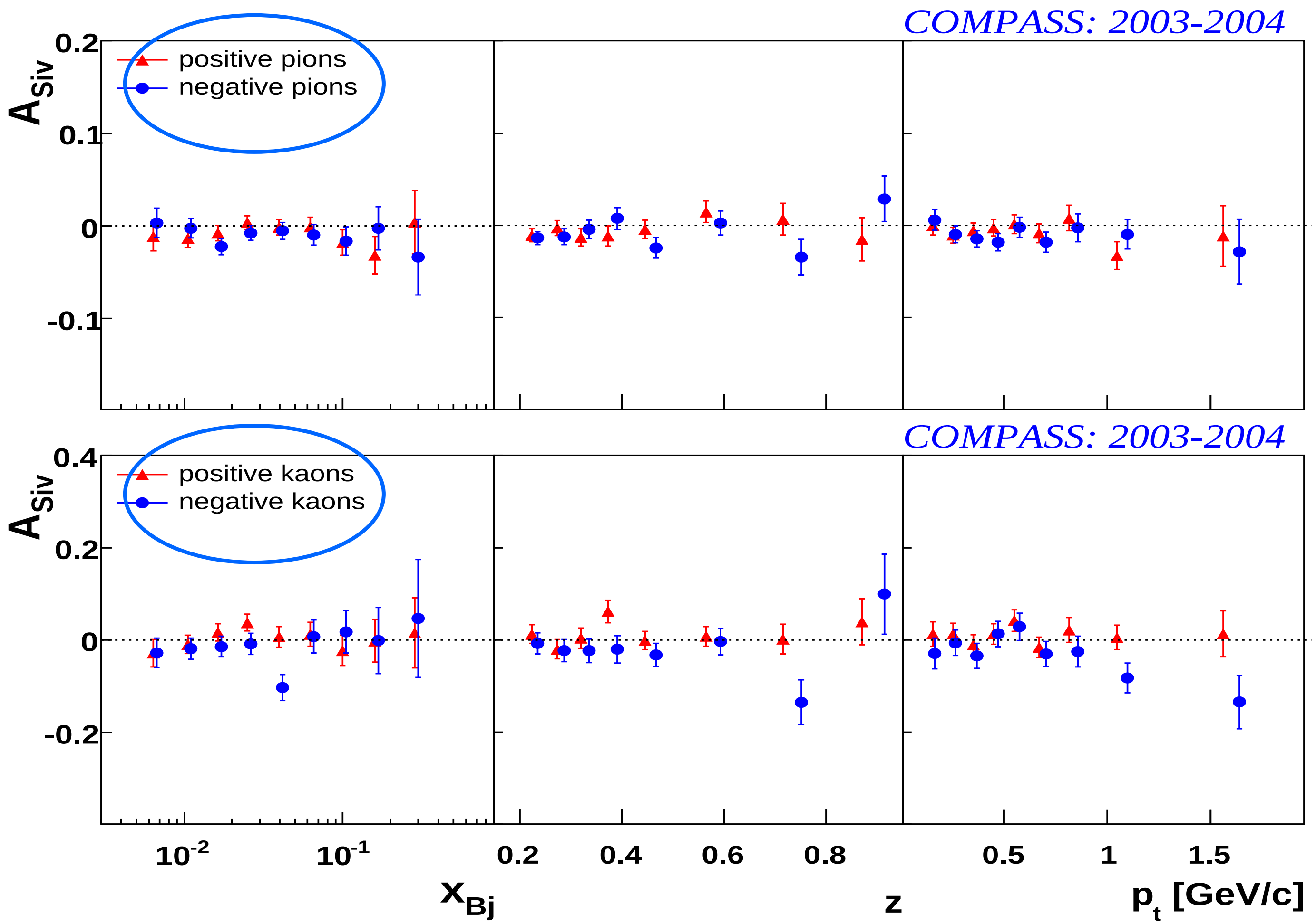
The Sivers DF $\Delta_0^T q$ is probably the most famous between TMDs… gives a measure of the correlation between the intrinsic transverse momentum of unpolarized quarks in a transversely polarized nucleon

In SIDIS the number of produced hadrons depend on the "Sivers angle":

$$N_h^{\pm}(\Phi_S) = N_h^0 \cdot \left\{ 1 \pm A_S^h \cdot \sin\Phi_S \right\} \qquad \Phi_S = \phi_h - \phi_s$$

$$A_{Siv} = \frac{A_S^h}{f \cdot P_T} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

Sivers asymmetries $\pi^{\pm}$ $K^{\pm}$



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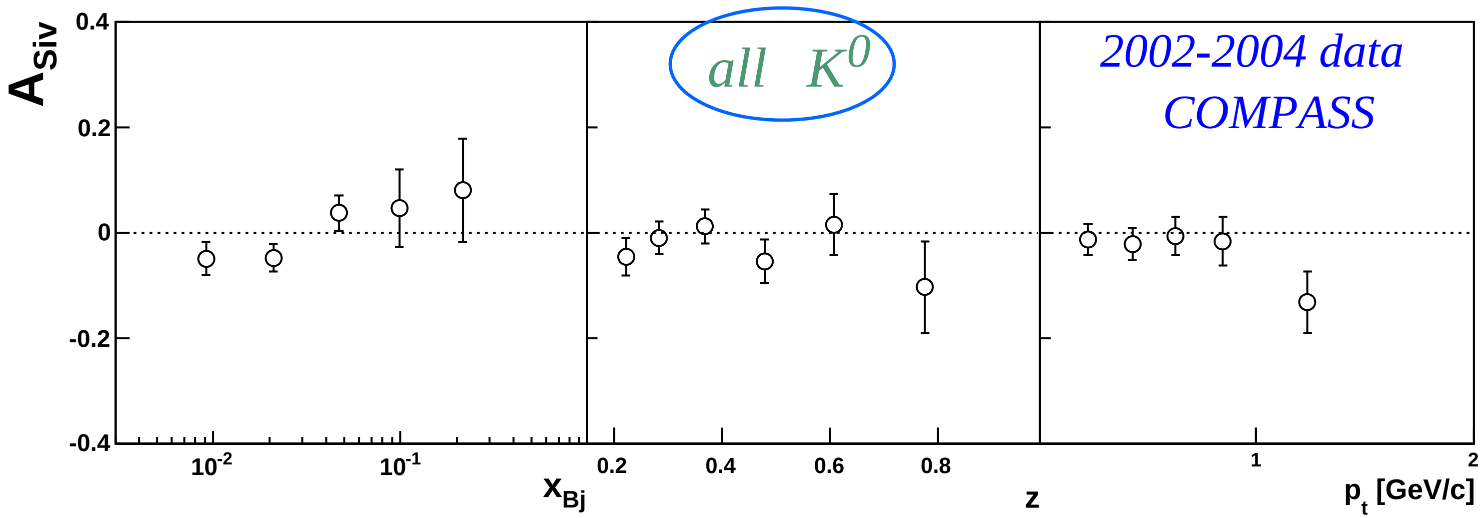

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$$A_{Siv}^{d,\pi^+} \simeq A_{Siv}^{d,\pi^-} \simeq \frac{\Delta_0^T u_v + \Delta_0^T d_v}{u_v + d_v}$$

Small asymmetries suggest $\Delta_0^T d_v \simeq -\Delta_0^T u_v$

- **the measured asymmetry on deuteron compatible with zero has been interpreted as**

Evidence for the Absence of
Gluon Orbital Angular Momentum in the Nucleon

S.J. Brodsky and S. Gardner, PLB643 (2006) 22

The approximate cancellation of the SSA measured on a deuterium target suggests that the gluon mechanism, and thus the orbital angular momentums carried by gluons in the nucleon, is small.

Other single spin asymmetries

In the complete SIDIS cross section more terms are present:
18 structure functions, 8 transverse target dependent spin asymmetries
with different azimuthal dependences

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\,\cdots\cdots$$

$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

$f_{1T}^{\perp q}\otimes D_{1q}^h$ **Sivers function**

$h_1^q\otimes H_{1q}^{\perp h}$ **Collins function**

All 8 asymmetries measured at COMPASS

From **A. Bacchetta** et al.,
JHEP 0702:093,2007. e-Print: **hep-ph/0611265**

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$f_{1T}^{\perp q} \otimes D_{1q}^{h}$ **Sivers function**

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$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ \cdots\cdots$$

$$+ |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \right)$$

$$+ \varepsilon \sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big]$$

$$+ |\boldsymbol{S}_\perp|\lambda_e \Big[\sqrt{1-\varepsilon^2}\, \cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_S\, F_{LT}^{\cos\phi_S}$$

$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\},$$

All 8 asymmetries measured at COMPASS

moreover results on Cahn asymmetries coming soon

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50% of the time dedicated to transverse measurements.
Major spectrometer improvement:
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•upgraded RICH (higher efficiency, better response)

First results coming soon ...

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Longer terms project (after 2010)
Plans for
•Precision SIDIS measurements for flavor separation
•Drell-Yan measurements (first test done during 2007 data taking)

backup

Other single spin asymmetries

$$F_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$F_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$F_{LT}^{\cos(\phi_s)} \propto \frac{M}{Q} g_{1T}^q \otimes D_{1q}^h$$

$$F_{LT}^{\cos(2\phi_h-\phi_s)} \propto \frac{M}{Q} g_{1T}^q \otimes D_{1q}^h$$

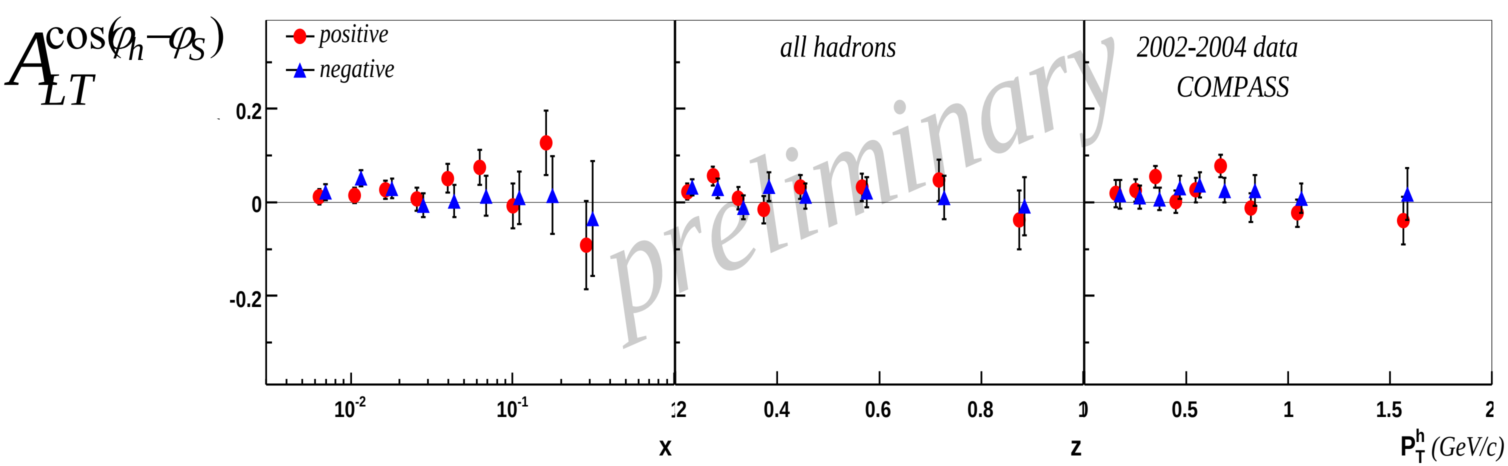
$$F_{UT}^{\sin(\phi_s)} \propto \frac{M}{Q}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h\right)$$

$$F_{UT}^{\sin(2\phi_h-\phi_s)} \propto \frac{M}{Q}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h\right)$$

Two twist-2 asymmetries can be interpreted in QCD parton model and will allow to extract unexplored DFs

Remaining four can be interpreted as twist-3 contributions

All asymmetries measured for the first time, found compatible with zero:
again cancellation between proton and neutron?



Lambda asymmetries

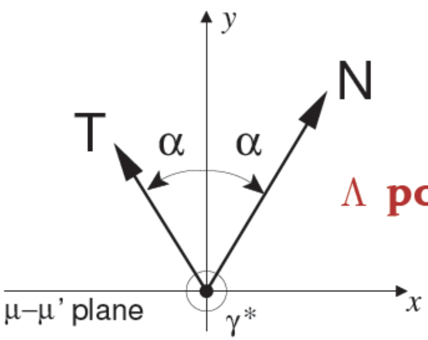
Information on $\Delta_T q$ can be accessed in the processes:

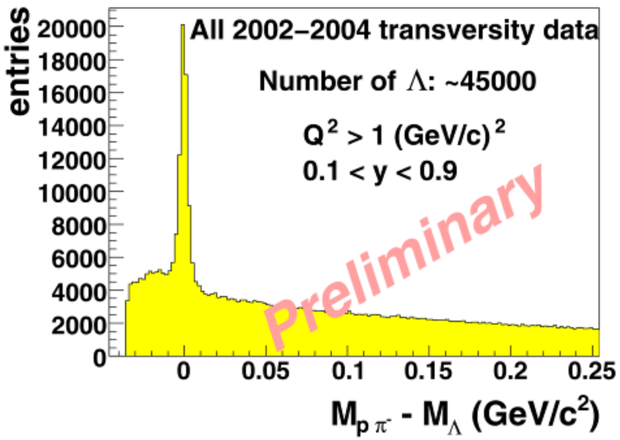
$$\mu\, N^{\uparrow} \rightarrow \mu'\, \Lambda\, X$$

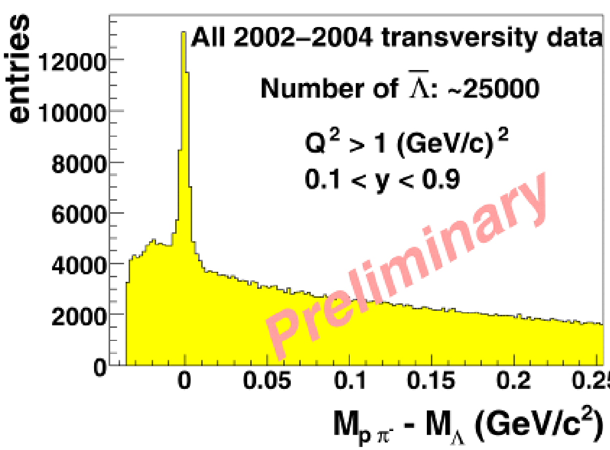
$$\mu\, N^{\uparrow} \rightarrow \mu'\, \overline{\Lambda}\, X$$

$$P^{\Lambda}_{T,exp} = \frac{d\sigma^{\mu N^{\uparrow}\rightarrow\mu'\Lambda^{\uparrow}X} - d\sigma^{\mu N^{\downarrow}\rightarrow\mu'\Lambda^{\uparrow}X}}{d\sigma^{\mu N^{\uparrow}\rightarrow\mu'\Lambda^{\uparrow}X} + d\sigma^{\mu N^{\downarrow}\rightarrow\mu'\Lambda^{\uparrow}X}}$$

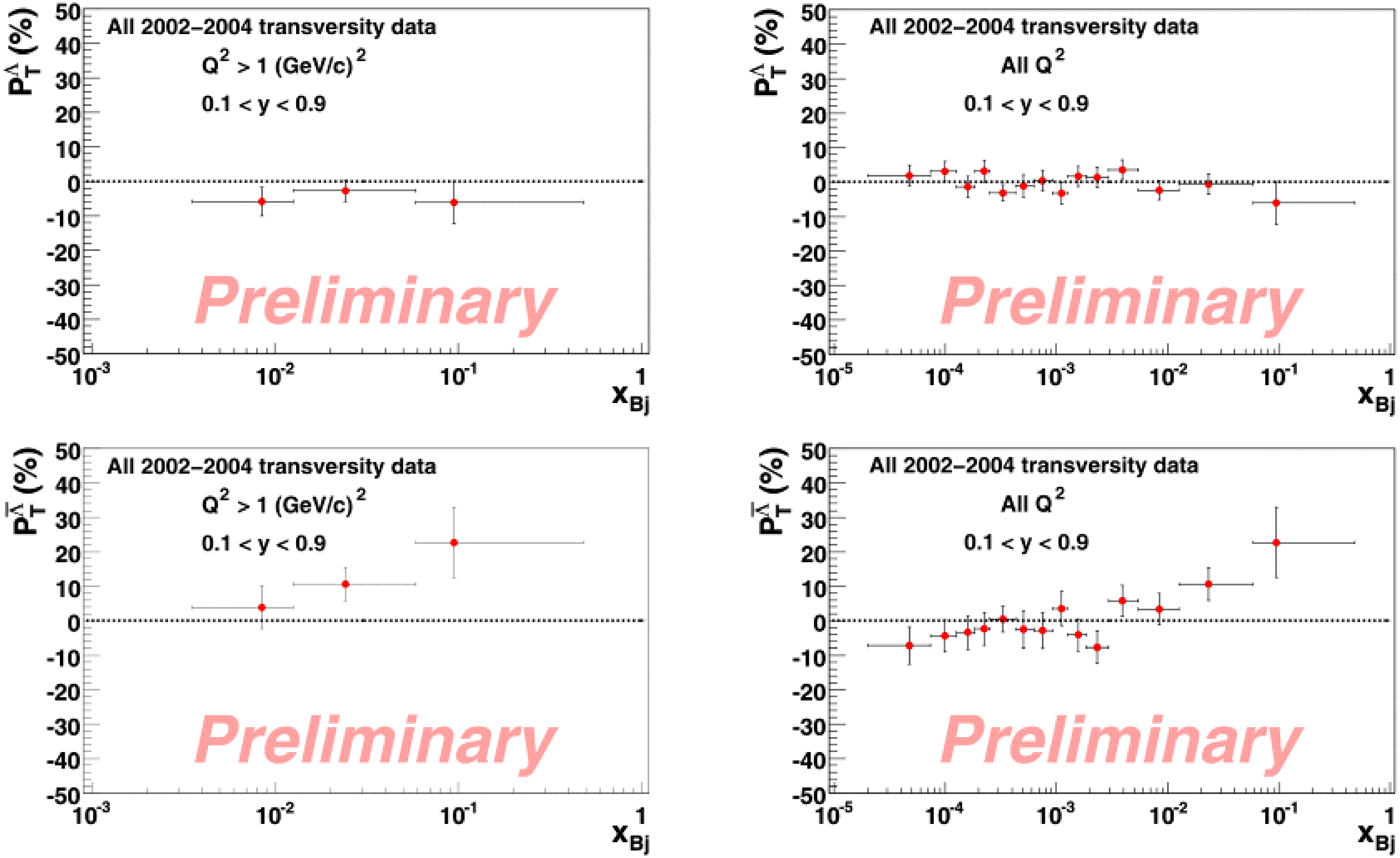
$$= f P_N D(y) \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)}$$







Lambda asymmetries



systematic errors not larger than statistical errors

RICH ID not used yet; someother improvement in selection still foreseen

Selection 2h

$$\vec{R} = \frac{z_1 \vec{P}_2 - z_2 \vec{P}_1}{z_1 + z_2}$$

DIS cuts:

- $Q^2 > 1\ GeV^2/c^2$
- $0.1 < y < 0.9$
- $W > 5\ GeV/c^2$

Hadron selection:

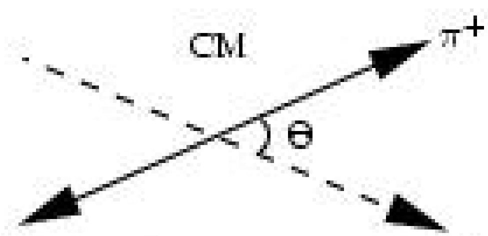
- $z_{1,2} > 0.1$ (current fragmentation)
- $x_{F1,2} > 0.1$
- $z_1+z_2 < 0.9$ (exclusive rho)
- RICH identification of π, K

sinθ dependance

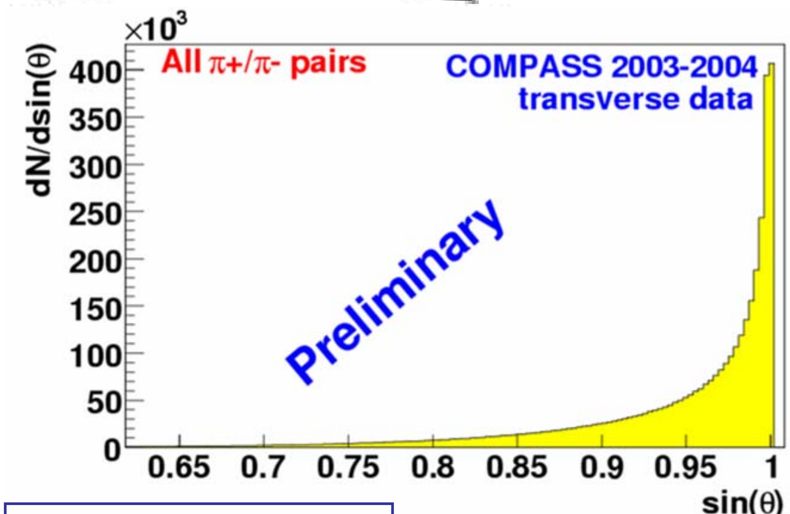
Cross section σ_{UT} for two-π fragmentation depends on sinθ:
(Interference of s- and p-wave of the 2π-state)

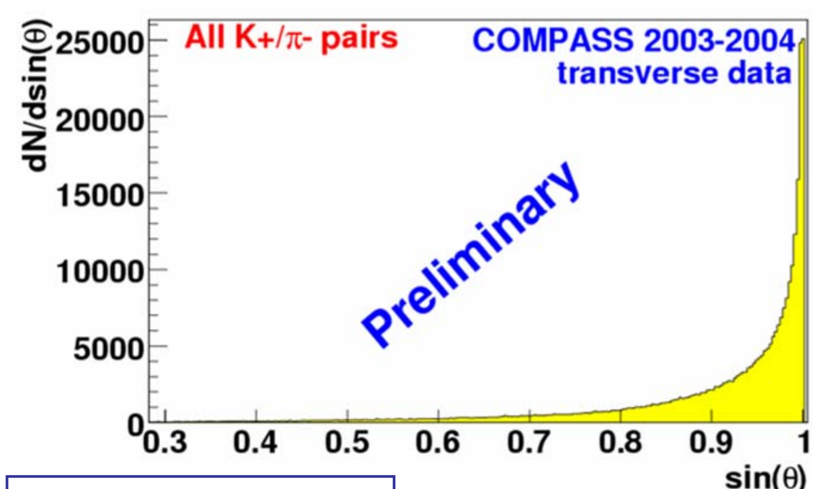
$$\sigma_{UT} \propto \sum_q e_q^2 \left|S_T\right| \sin\theta \sin\phi_{RS} \Delta_T q(x) H_q^{\perp\angle h}(z, M_h^2)$$

(A. Bacchetta and M. Radici, hep-ph/0212300)



θ : Angle of h_1 in the two-hadron CMS to the direction of $P_h = P_{h1} + P_{h2}$





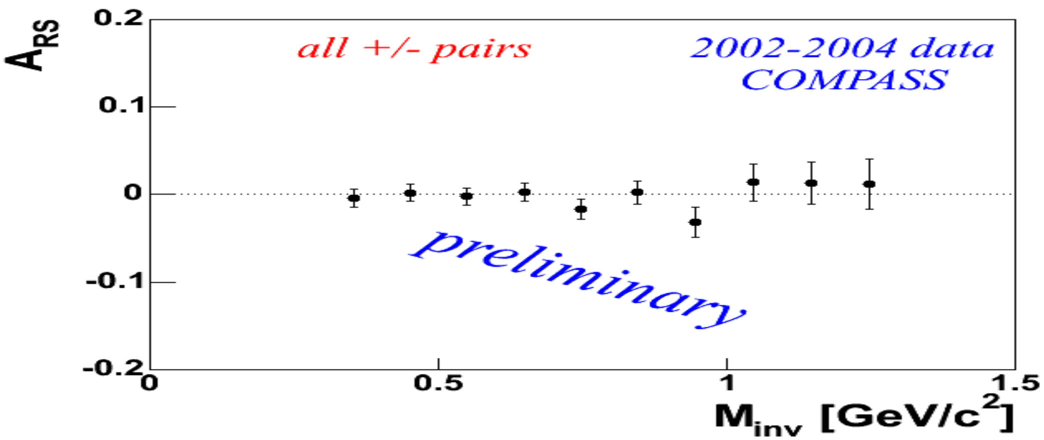
<sinθ> = 0.95

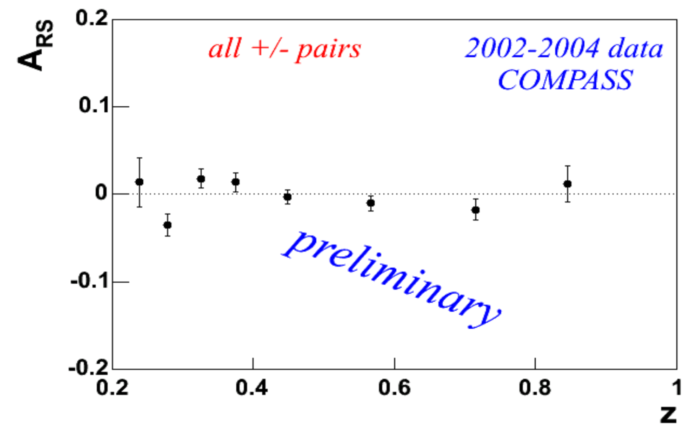
<sinθ> = 0.90

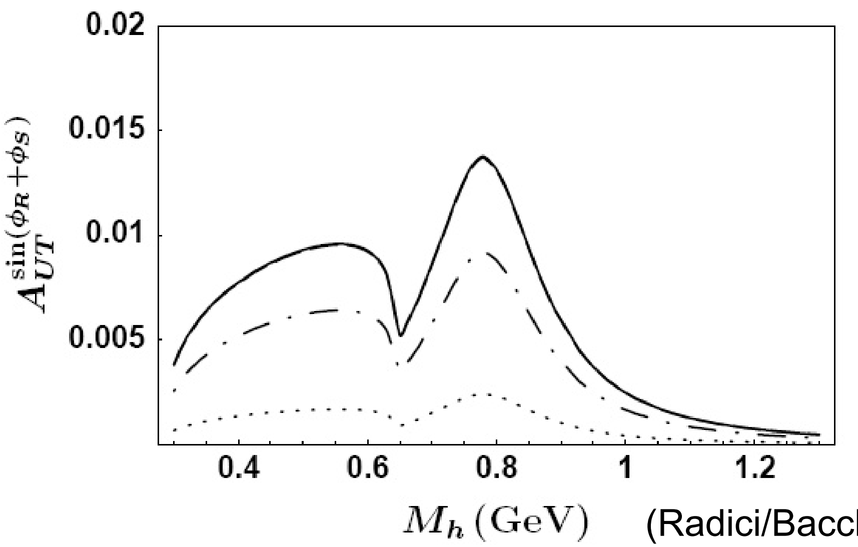
➔ small contribution in the kinematic region of COMPASS

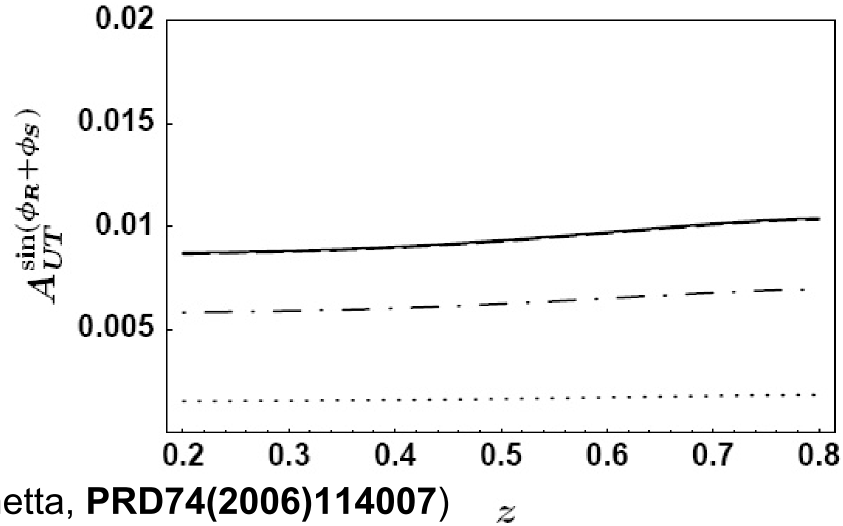
Two hadron asymm.s

Expected Small

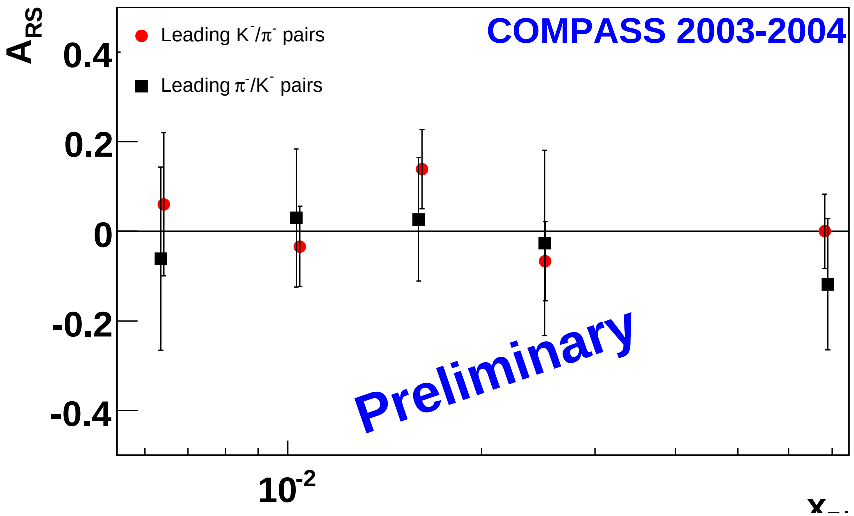




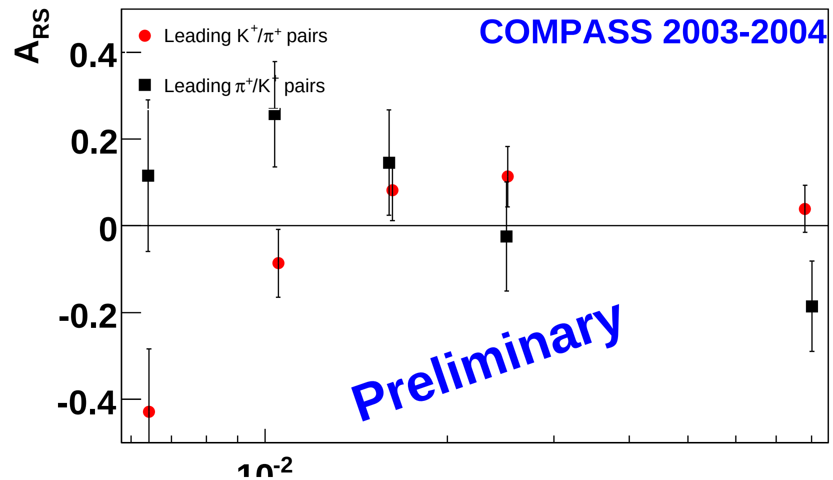




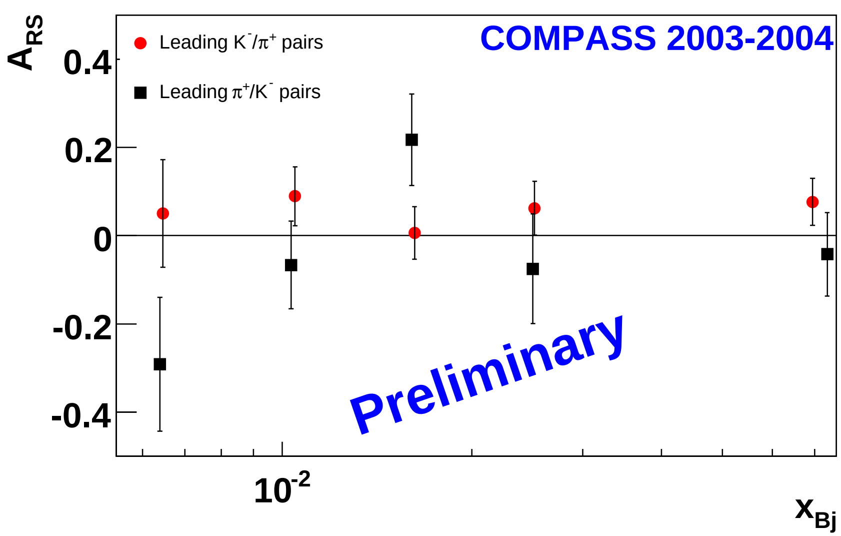
(Radici/Bacchetta, **PRD74(2006)114007**)



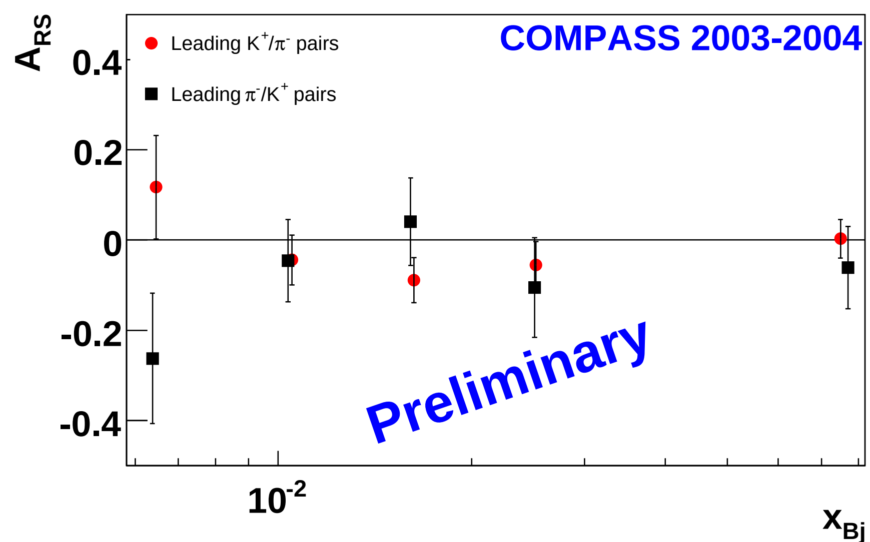
A_{RS}
Leading K^-/π^- pairs
Leading π^-/K^- pairs
COMPASS 2003-2004
Preliminary
0.4
0.2
0
-0.2
-0.4
10^{-2}



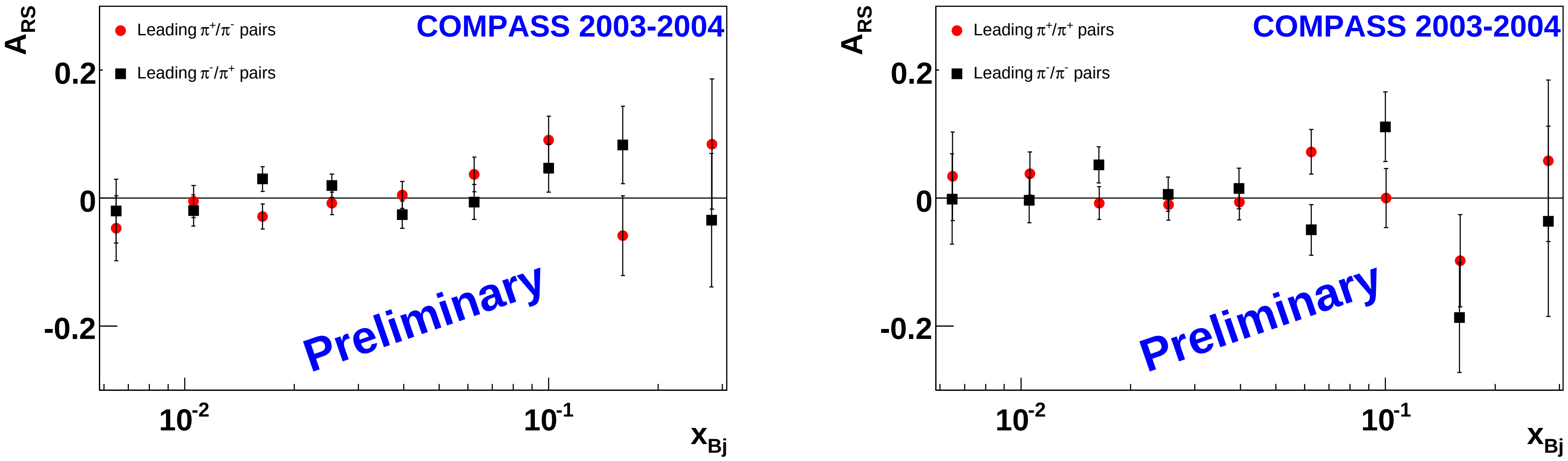
A_{RS}
Leading K^+/π^+ pairs
Leading π^+/K^+ pairs
COMPASS 2003-2004
Preliminary
0.4
0.2
0
-0.2
-0.4



A_{RS}
Leading K^-/π^+ pairs
Leading π^+/K^- pairs
COMPASS 2003-2004
Preliminary
0.4
0.2
0
-0.2
-0.4
10^{-2}
x_{Bj}



A_{RS}
Leading K^+/π^- pairs
Leading π^-/K^+ pairs
COMPASS 2003-2004
Preliminary
0.4
0.2
0
-0.2
-0.4
10^{-2}
x_{Bj}


A_RS
Leading π+/π- pairs
Leading π-/π+ pairs
COMPASS 2003-2004
0.2
0
-0.2
Preliminary
10-2
10-1
x_Bj
A_RS
Leading π+/π+ pairs
Leading π-/π- pairs
COMPASS 2003-2004
0.2
0
-0.2
Preliminary
10-2
10-1
x_Bj

Transverse Target SSA for exclusive ρ ($Q^2>1$)

- Motivations:
  - Hard exclusive meson production (HEMP) is a way, complementary to DVCS, to access GPDs
  - Vector mesons Transverse Target Single Spin Asymmetry $A_{UT}(\phi_h,\phi_S)$ connected to GPD E

Ji Sum Rule

$$\frac{1}{2}\sum_q \int_{-1}^{+1} dx\, x(H^q(x,\xi,t=0)+E^q(x,\xi,t=0)) = J^{quark}$$

  - E allows flip of proton helicity, while quark helicity is not flipped → overall helicity is not conserved
  - angular momentum conservation implies transfer of orbital angular momentum

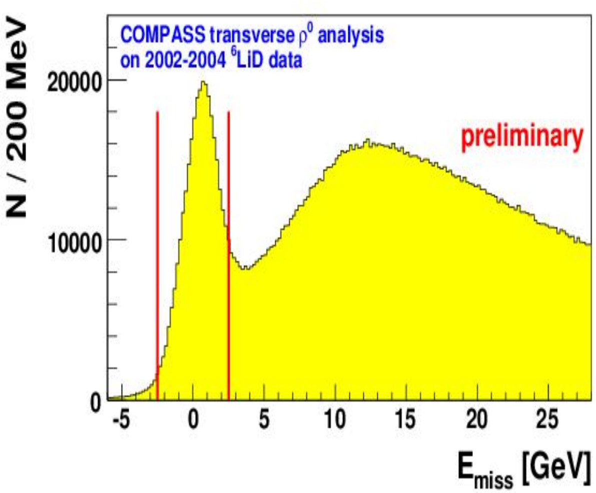
Selection

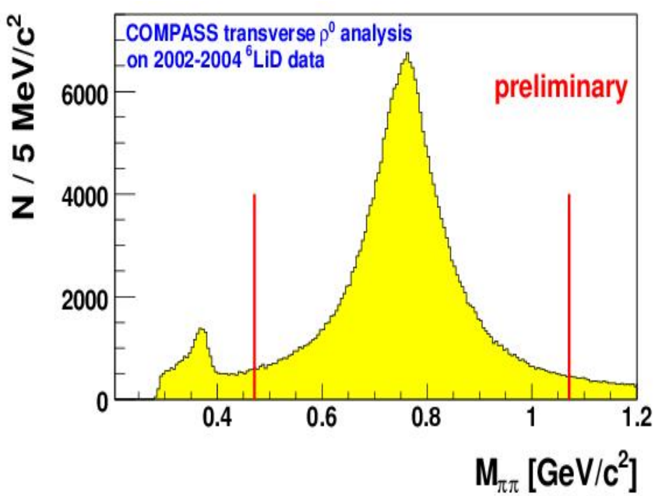
Besides standard DIS cuts:

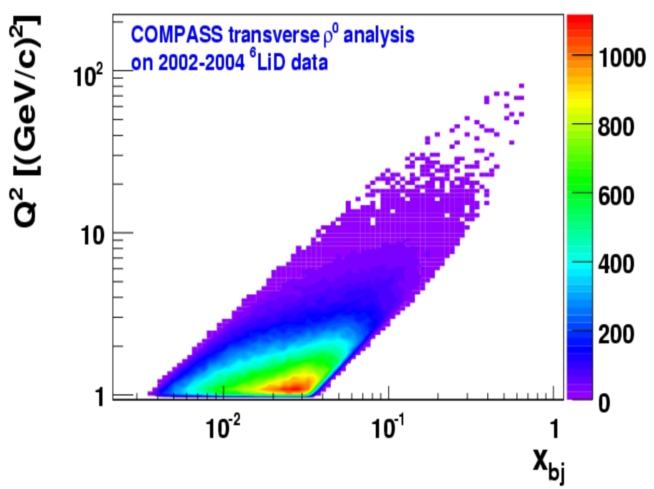
- $Q^2 > 1\ GeV^2/c^2$
- $0.1 < y < 0.9$
- $W > 5\ GeV/c^2$

Exclusive ρ selection:

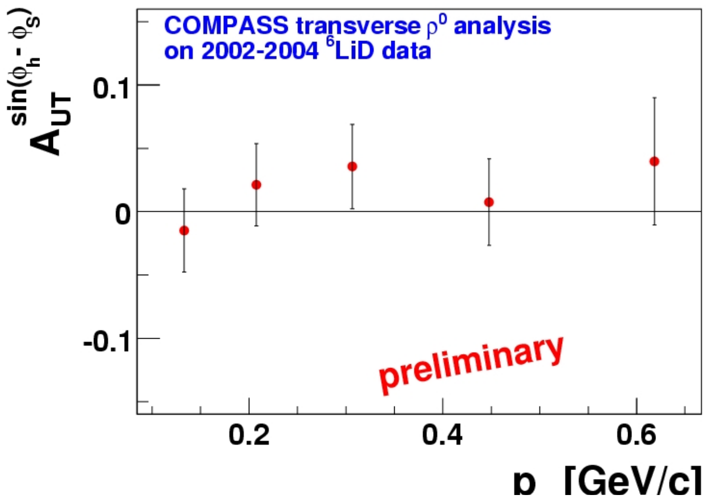
- only 3 outgoing particles μ, π^+, π^-
- $0.01 < p_T^2 < 0.5\ [(GeV/c)^2]$
- missing energy $-2.5\ GeV < E_{miss} < 2.5\ GeV$
- Inv. Mass $-0.3\ MeV/c^2 < M_{\pi\pi} - M_\rho < 0.3\ MeV/c^2$

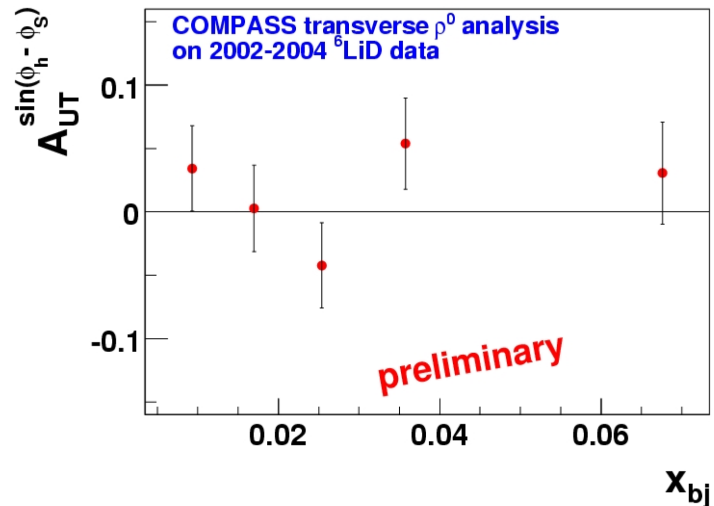


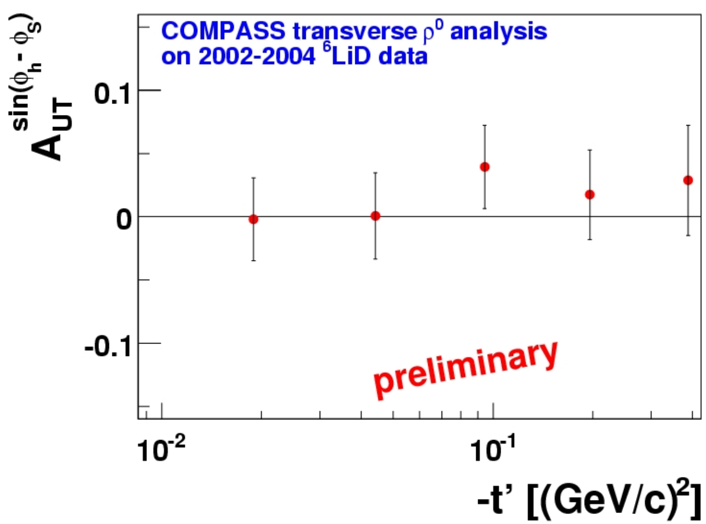


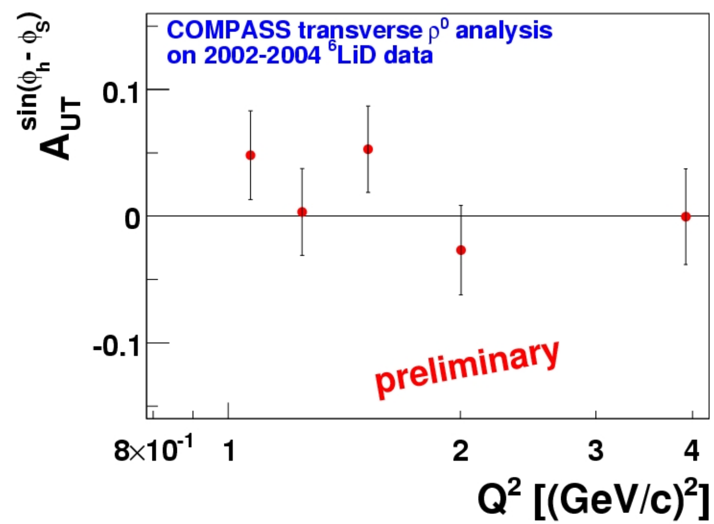


Results


COMPASS transverse ρ0 analysis
on 2002-2004 6LiD data
$A_{UT}^{\sin(\phi_h - \phi_S)}$
0.1
0
-0.1
preliminary
0.2
0.4
0.6
p [GeV/c]


COMPASS transverse ρ0 analysis
on 2002-2004 6LiD data
$A_{UT}^{\sin(\phi_h - \phi_S)}$
0.1
0
-0.1
preliminary
0.02
0.04
0.06
x_{bj}


COMPASS transverse ρ0 analysis
on 2002-2004 6LiD data
$A_{UT}^{\sin(\phi_h - \phi_S)}$
0.1
0
-0.1
preliminary
10^{-2}
10^{-1}
-t' [(GeV/c)2]


COMPASS transverse ρ0 analysis
on 2002-2004 6LiD data
$A_{UT}^{\sin(\phi_h - \phi_S)}$
0.1
0
-0.1
preliminary
8×10^{-1}
1
2
3
4
Q^2 [(GeV/c)2]

Data taking and stability of the data

Look for very small effects
→data stability is a crucial issue

Many tests done to check the data stability:
• monitor the stability in time of reconstructed K^0 mass and RMS, K^0 multiplicity
• spectrometer time stability
• stability of kinematical variables

Other specific tests for RICH detector